

# **Mixing, Internal Waves and Mesoscale Dynamics in the East China Sea**

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## **LONG TERM GOAL**

The long-term goal of our research program is to better understand and quantify relationships between mesoscale dynamics, internal waves, and turbulence in shallow, tidally-affected seas.

## **OBJECTIVES**

The objectives of the third year of the project were:

- (i) to determine the characteristics of microstructure and internal waves in the Yellow Sea (YS) at the end of the warming season when the stratification is favorable for generation of internal solitons of elevation (i.e. the surface boundary layer is thicker than the bottom layer whilst the pycnocline is narrow and sharp), and
- (ii) to obtain further observational information on the genesis of high-frequency non-linear internal waves packets and solitons during a specific phase of the barotropic tide, the period of interest being close to the low tide in the central East China Sea (ECS) and YS.

## **APPROACH**

1. Analysis of field data obtained in 2006 in ECS and YS during two research cruises carried out in August by the Korea Ocean Research and Development Institute (KORDI) and in September by the Ocean University of China (OUC).
2. Conducting new field campaigns: by OUC in the central YS with CTD, ADCP, and ADV measurements taken at the same locations as in 2006; and by KORDI in the southeastern part of ECS, closer to the ocean shelf break.

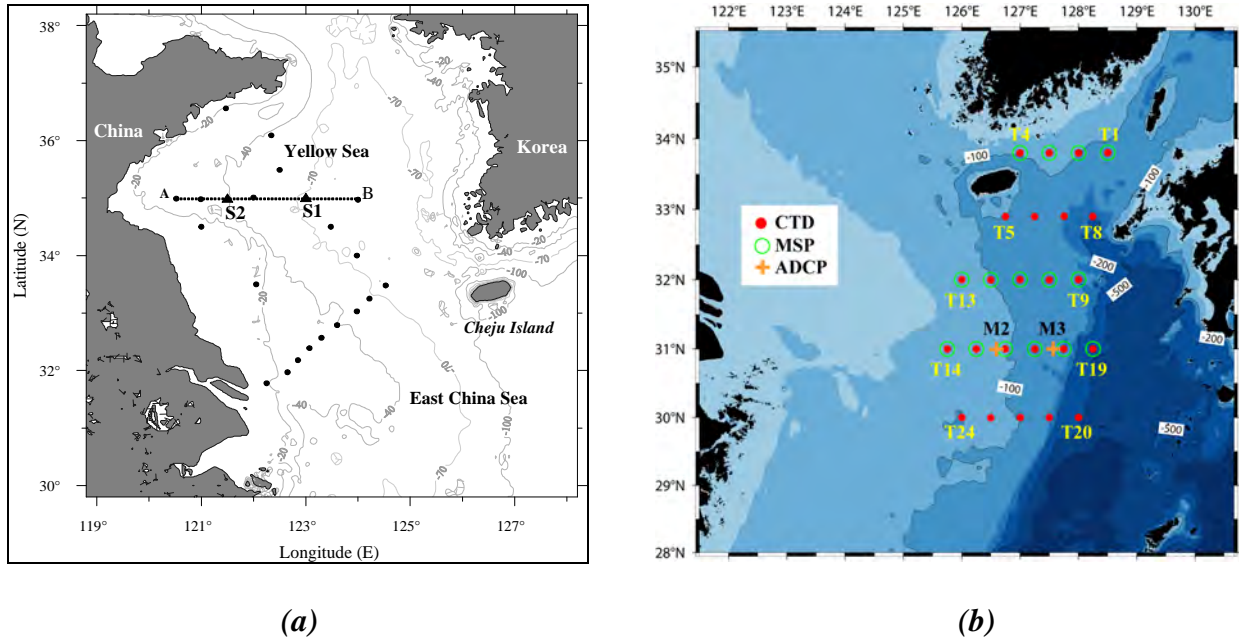
## **WORK COMPLETED**

### **Field Campaigns**

The new research cruise of OCU was conducted during August 8 - 15, 2007 in the same region of YS as it was in September 2006 (Fig. 1a). This year, however, the data from two bottom mounted, upward looking ADCPs were obtained at both mooring stations **S1** (deeper basin) and **S2** (local shelf break) rather than only at **S2** in 2006. At the shallower station **S2**, an RDI 600 kHz ADCP was mounted at the bottom to continuously measure the velocity components through the water column, with a sampling interval of 2 s and a cell size 0.75m. Preliminary assessment of data quality showed that the

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ADCP tilts were  $< 2$  degree. In addition, a Nortek 6MHz ADV instrument was bottom-mounted at **S2** to measure turbulent fluctuations near the bottom. The data were registered at 8-min burst intervals with a sampling rate of 16 Hz over burst duration of 256 s. The sampling volume was at 0.3 m above the seafloor. At the deeper station **S1**, a 1200 kHz RDI ADCP collected data with a high vertical resolution (2 cm cell size). Unfortunately, the data from another ADCP at this location were found to be corrupted due to malfunction of the instrument. The Seabird SBE-25 and the RBR XR-620 instruments were used for the CTD profiling. No microstructure measurements have been carried out during the cruise.



**Fig. 1: (a) - 2006 and 2007 cruises of OUC; CTD stations are shown by dots. ADCP and ADV measurements were conducted at stations S1 and S2, which are at the section AB along 35°N. (b) – 2007 cruise of KORDI: The type of measurements is given in the legend.**

A CTD survey (24 stations) was conducted in ECS by KORDI on August 18 - 24, 2007 (Fig. 1b). During this cruise, turbulent measurements were carried out using a TurboMAP microstructure profiler (MSP) at 15 stations marked in Fig. 1b. Two bottom-mounted ADCPs were also setup in the center of the observational region (see Fig. 1b) to capture the flow dynamics, including high-frequency internal waves during various phases of the barotropic tide. The survey area was extended to the ocean shelf break where intense internal waves and internal tides are usually generated. The obtained data are being subjected to quality assurance and preliminary processing, and will be available for formal analysis shortly.

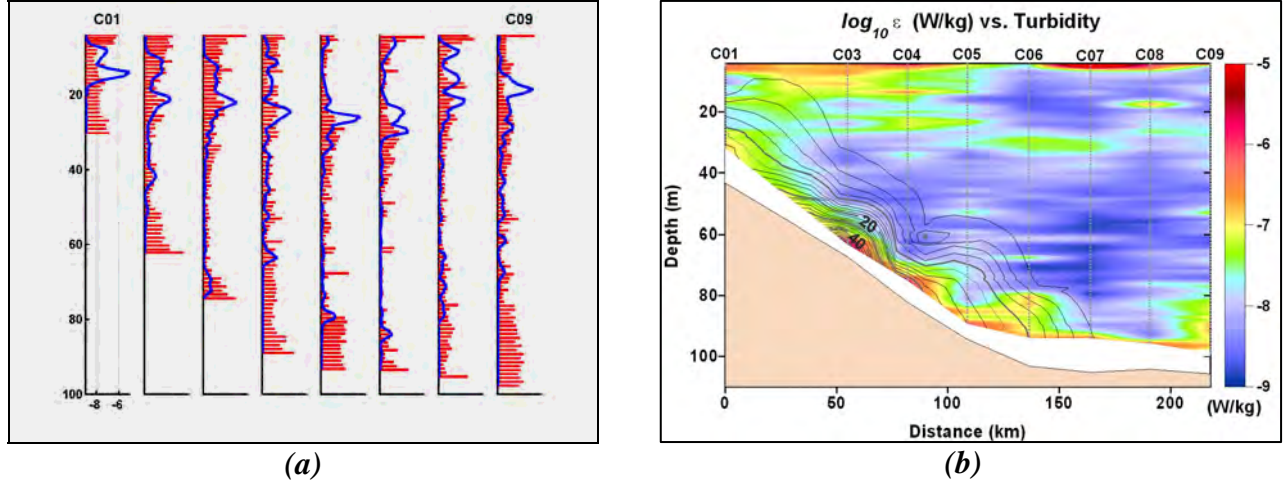
## RESULTS

### Near-Bottom Mixing in the East China Sea:

#### *A Preliminary Analysis of 2006 KORDI Cruise*

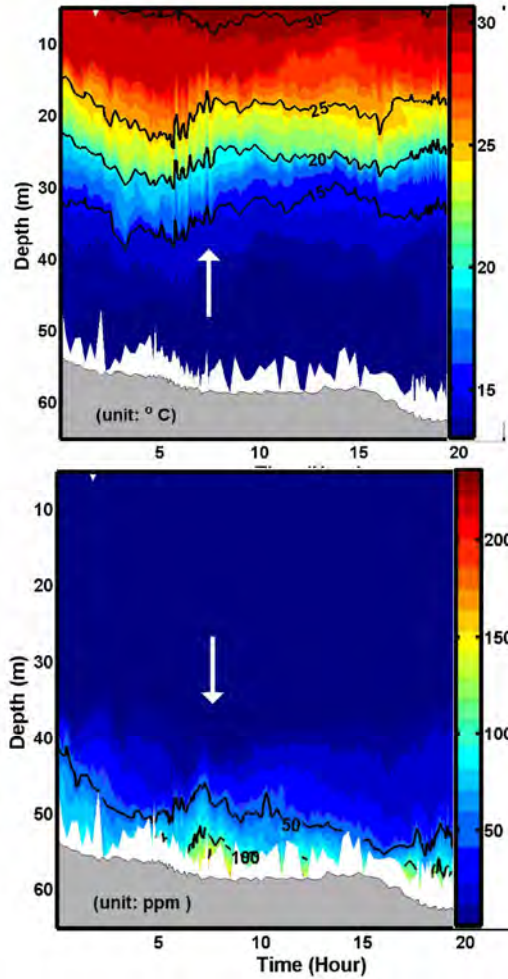
In August 2006, the height of the bottom mixed layer south of the Cheju Island (Fig. 1b) varied over 5 - 15 m; the dissipation of the turbulent kinetic energy  $\varepsilon$  in the BBL was  $O(10^{-7} \text{ W/kg})$ , but episodically

it increased to  $\sim 10^{-6}$  W/kg. The corresponding vertical eddy diffusivity  $K_N = 0.2\varepsilon/N^2$ , where  $N$  is the buoyancy frequency, could reach  $10^{-2}$  m<sup>2</sup>/s (Fig. 2). High values of  $\varepsilon$  and  $K_N$  were consistent with the enhanced turbidity near the bottom, specifically at shallow depths (see Fig. 2b). The multiple MSP profiles and data taken from a ship-mounted ADCP showed a good correlation between the variability of the bottom mixed-layer height and variations of the magnitude of tidal currents. This suggests that vertical mixing in the bottom layer was mainly driven by tidal stirring at the seafloor. The same dependence of the BBL height versus amplitude of tidal vector was also observed on the Chinese shelf of ECS (reported in Lozovsky et al. 2007a).



**Figure 2. (a) The profiles of  $\varepsilon(z)$  along the NW-SE section in ECS southwest of the Cheju Island; (b) the contours of turbidity (grey lines) overlaying the cross-section of the dissipation rate (color pallet).**

As was in the 2005 KORDI field study (Lee et al., *GRL* 33, L18601, 2006), packets of high-frequency nonlinear internal waves (NLIW) were registered in August of 2006 during the phase of low tide in the region (see Fig. 3). The ADCP data revealed high-frequency fluctuations of all components of the velocity vector across the entire water column, suggesting the possibility of vertical transport of salinity, nutrients and dissolved matter between the layers. The time of propagation of one of the NLIW packets shown in the upper panel of Fig. 3 correlated well with the period of enhanced turbidity in the bottom mixed layer (see Fig. 3, lower panel). The generation of a higher turbidity zone near the seafloor occurred with a slight time delay relative to the appearance of NLIW in the pycnocline. All of these observations suggest that in shallow seas NLIW can substantially influence the dynamics of near-bottom boundary layer. An increase of sediment suspension from the seafloor up to  $\sim 10$  m into the water column and enhancement of momentum transfer and turbulence are expected by such waves.

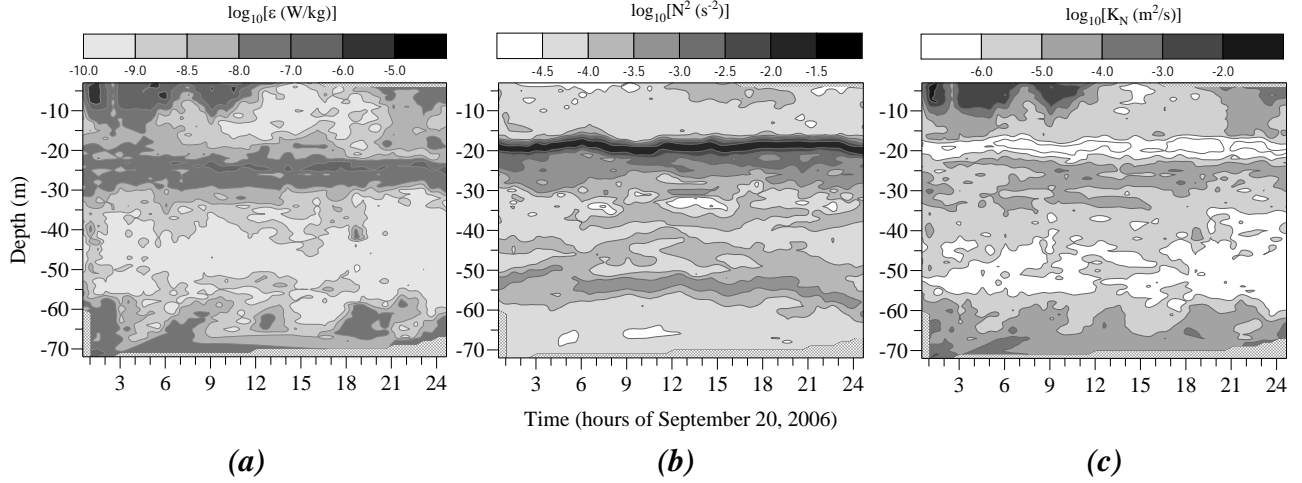


*Figure 3. Vertical distribution of temperature (upper panel) and turbidity (lower panel) during 20 hours of measurements at a drift station in August 2006. The arrows point to the NLIW packet in the thermocline (up) and a higher-turbidity zone in the BBL (down).*

### ***B. Turbulence in the Yellow Sea: Results of 2006 OUC cruise.***

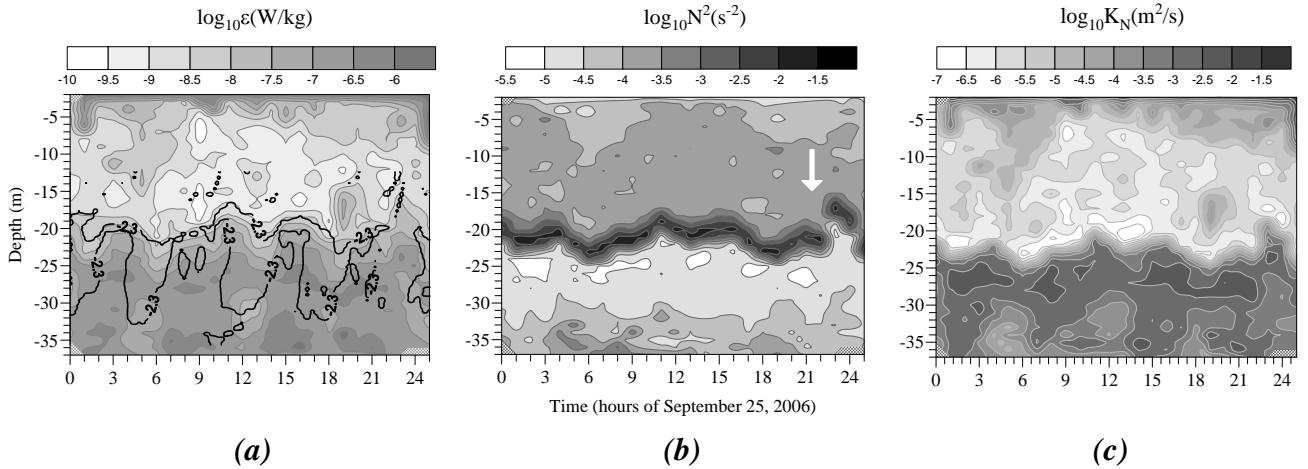
During the 2006 field campaign in the Yellow Sea, which included microstructure profiling at **S1** and **S2** (Fig. 1a), two distinct regimes of turbulence and mixing were observed in the background of late summer stratification. One station was located in the deeper central basin and the other near a local shelf break at the same latitude, 35°N. The microstructure measurements at the shallower station were augmented by the bottom-mounted ADCP.

Weakly stratified surface and bottom boundary layers separated by a narrow pycnocline were observed at the end of the warm season. Under weak winds, the surface-layer turbulence was mainly driven by the diurnal cycle of buoyancy flux at the sea surface (higher mixing at night and vice versa).



**Figure 4.** The variation of the logarithms of the kinetic energy dissipation rate  $\log_{10} \varepsilon$  (a); squared buoyancy frequency  $\log_{10} N^2$  (b); and eddy diffusivity  $\log_{10} K_N$  (c) at S1.

Unlike in wintertime, whence the stratification is destroyed by stormy winds and deep convection (Lozovatsky et al., 2007a,b), no influence of tidal forcing (tidal shear) was detected in the upper layer. The bottom stress due to barotropic tidal currents, however, dominated the nature of turbulence near the seafloor. In the deep (73 m) waters of the YS central basin, enhanced rate of dissipation  $\varepsilon$  and vertical diffusivity  $K_N$  were observed up to  $\zeta = 10$ -15 m above the bottom (Fig. 4).



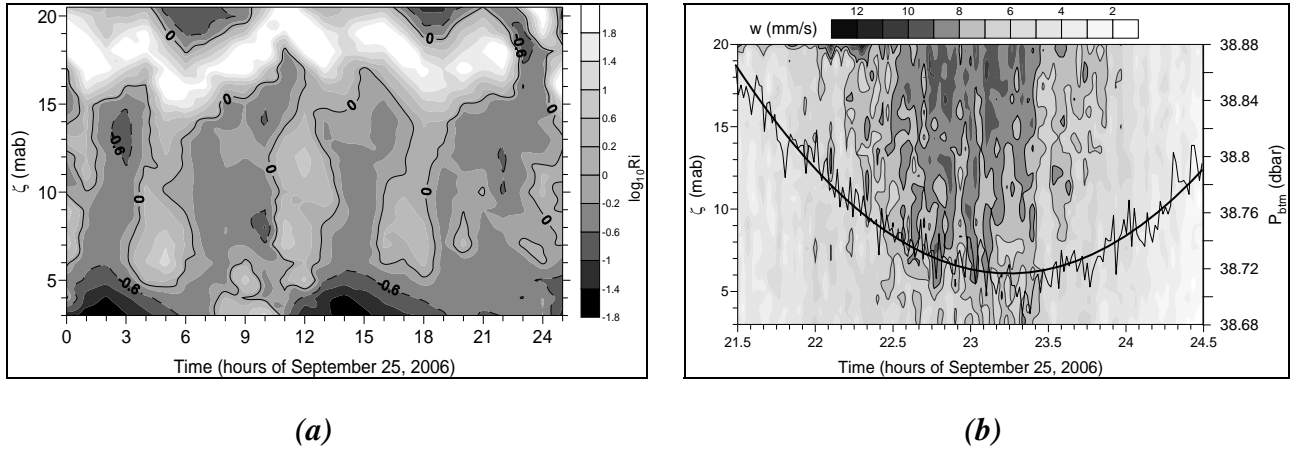
**Figure 5.** Variations of the logarithms of the kinetic energy dissipation rate  $\log_{10} \varepsilon$  overlaid by the marked contours of shear  $\log_{10} Sh = -2.2 \text{ s}^{-1}$  (a); the squared buoyancy frequency  $\log_{10} N^2$  (b); and the eddy diffusivity  $\log_{10} K_N$  (c) at S2. The arrow in panel (b) points to the pycnocline displacement presumably caused by an internal wave soliton of elevation.

At shallower depths (38 m) near the local shelf break, the tidally induced turbulence completely occupied the lower part of the water column (Fig. 5) up to the pycnocline (the distance  $\zeta \sim 15$ -18 m above the seafloor). A quarter-diurnal periodicity of an increase/decrease of  $\varepsilon$  (the range of variations

$5 \times 10^{-8} - 5 \times 10^{-6}$  W/kg) and  $K_N$  ( $10^{-5} - 10^{-2}$  m<sup>2</sup>/s) was observed at different heights  $\zeta$  with a time lag of  $\sim 5$ -6 m/hr. The Richardson number in the lowest 8 meters was below unity  $\sim 70\%$  of the time, and  $\sim 20\%$  of the time it was less than 0.25, indicating combined effects of shear and internal-wave instabilities near and above the seafloor.

During the observational period, the deep-water pycnocline in the central basin was essentially non-turbulent, and no internal-wave activity was detected. As such, vertical fluxes across the pycnocline decreased to molecular levels, thus impeding vertical exchange of nutrients and oxygen between the surface and bottom boundary layers that could negatively affect bio-chemical balance in the region.

On the other hand, internal waves of numerous periods were observed throughout the whole water column near the shelf break. Quasi-sinusoidal waves of  $\sim 43$ , 18, 14, and 11 min periods produced salient peaks in the energy spectra of horizontal tidal residuals, especially closer to the seafloor. In the pycnocline, intermittent turbulence appeared, preceded by short periods of the decrease of Richardson number  $Ri$  possibly due to internal wave breaking. A sharp displacement of the pycnocline with amplitude  $\sim 4$ -5 m, observed during the low tide, could be attributed to an internal solitary wave (the event is pointed by an arrow in Fig. 5b).



**Figure 6.** (a) - the Richardson number at S2. A quarter-diurnal periodicity of the regions with  $Ri < 1$  and  $Ri > 1$  is highlighted by the contour  $\log_{10}(Ri) = 0$ . Note a dark strip of low  $Ri$  at  $t \sim 23$  hr above  $\zeta > 14$  mab that “penetrates” the pycnocline (light-colored zone above  $\zeta = 15$  mab). This is possibly due to the instability of an internal wave soliton, which can be seen in panel (b) in the vertical velocity contour plot. The near-bottom pressure given in (b) by a thin line indicates that the soliton emerged in the phase of low tide.

The larger thickness of the upper layer compared to the lower layer appears to create favorable conditions for the generation of a soliton of elevation near the shelf break (Fig. 6b). The enhanced shear associated with this internal soliton has led to  $Ri < 1$  and even  $Ri < 0.25$  across the pycnocline (Fig. 6a), which in turn increased the turbulence level. The dissipation observed at the beginning of the event,  $\varepsilon = 2 \times 10^{-8}$  W/kg, was more than ten times the background level observed before and after the emergence of the soliton.



## IMPACT/APPLICATION

Our research program has been greatly strengthened by the international collaboration with Korean and Chinese oceanographers. The PIs have had productive meetings this summer with co-PI Dr. Jae Hak Lee of KORDI, where detailed plans for a future field campaign in the ECS as well as strategies of data analyses were discussed. Two joint papers with the OUC colleagues have been accepted for publications in the Journal of Continental Shelf Research and another paper was submitted to a special issue of Journal of Marine Systems. I. Lozovatsky presented the results at the 39<sup>th</sup> International Liege Colloquium, “Ocean Turbulence, Re-revisited” in May, Belgium and co-PI J.-H. Lee made presentations at the XXIV IUGG General Assembly in July, Italy and at the 14<sup>th</sup> PAMS/JECSS Workshop in May, Japan.

## TRANSITIONS

None

## RELATED PROJECTS

The Co-P.I. Fernando is involved in another ONR funded project dealing with laboratory investigations of surface waves in coastal zone, their breaking and interacting with solid objects. This project is funded by the Coastal Geosciences Program of the ONR.

## PUBLICATIONS

Lozovatsky, I.D., Z. Liu, H. Wei, and H.J.S. Fernando, Tides and mixing in the northwestern East China Sea. Part I: Rotating and reversing tidal flows. *Continental Shelf Research*, doi:10.1016/j.csr.2007.08.006, 2007a.

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